R & D of the Next-generation marine gas turbine (Super Marine Gas Turbine)

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1. Introduction

In 1997, five Japanese gas turbine makers (KHI, IHI, Daihatsu Diesel, Niigata Engineering and Yanmar Diesel) jointly established a six-year plan to conduct R&D on a low-NOx, high-efficiency, next-generation marine gas turbine （SMGT）. The project is supported by the Ministry of Transport, the Association for Structural Improvement of the Shipbuilding Industry and the Nippon Foundation. This paper presents an outline of the SMGT and the latest results of the research.

2. R&D Background

As awareness of global environmental problems grows, methods of reducing air pollution caused by ships are attracting increasingly intense interest around the world. In 1997, the International Maritime Organization (IMO) adopted a new amendment to the MARPOL agreement regarding reduction of atmospheric pollution caused by shipping, which established NOx emission levels after the year 2000. These standards are expected to become even more stringent in the years to come.

With an emergent recognition of the need for advancements in the maritime transport field, coastal shipping in particular is in need of more modern ships – vessels which will not only lower coastal pollution levels, but also deliver higher speeds and reduce on-board labour requirements. With its compact size, light weight, low vibration levels, relatively quiet operation and ease of maintenance, the gas turbine has the potential to meet all these criteria. Due to method of combustion, the gas turbine produces significantly lower NOx emissions than a diesel engine, and it is widely recognized that if gas turbines were widely used as ship engines, the resultant reduction in NOx emissions would be dramatic.

However, due to high fuel consumption and other cost-related concerns, applications for gas turbines as marine engines have until now been limited.

By creating a next-generation marine gas turbine which offers both significantly reduced NOx emissions *and* dramatically improved fuel economy over conventional gas turbines, this project hopes to overcome the drawbacks currently associated with gas turbines and allow for their much broader application as marine engines.

3. R&D Goals

3.1) Overall Goals

The SMGT is a 2,500 kW class gas turbine designed mainly for use as a main engine for coastal shipping. It is being developed to meet the following three goals:

1. NOx emissions of less than 1g/kWh
2. Thermal efficiency of 38~40%
3. Feasibility to use fuel oil type A (JIS K2205 No.1)

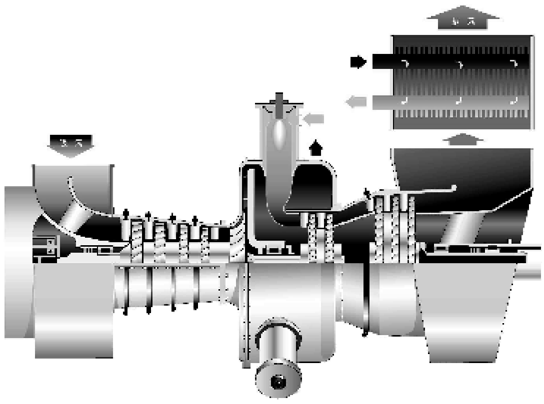


Fig.1 Conceptual Drawing of SMGT

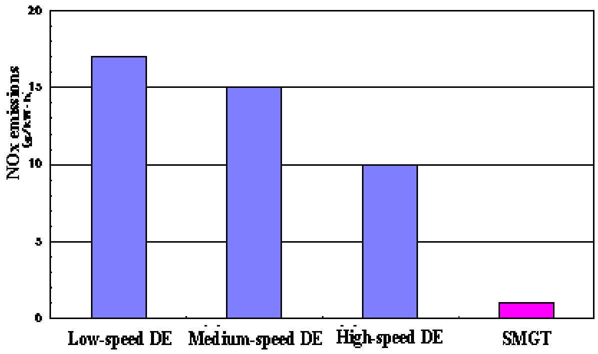


Fig.2 Comparison of NOx emissions

NOx emissions are about one-tenth those of diesel engines. Thermal efficiency is approximately the same as that of high-speed diesel engines. When these target figures are compared with those of conventional gas turbines of the same output class, they represent a one-third reduction in NOx emissions (liquid fuel combustor) and a 10% improvement in thermal efficiency, for a 30% improvement in fuel consumption.

Further, in relation to the availability of ship fuel, the SMGT is being designed to permit use of fuel oil type A.

3.2) R&D Items

To achieve the above goals, the following main items are being researched:

3.2.1) Research to Reduce Environmental Impact

One way to reduce N0x emissions of gas turbines is to lower the combustion temperature by the wet method of injecting water or steam into the combustor. However, this is unsuitable for marine use because it requires large amounts of clean water. Accordingly, we are developing a dry, low NOx combustor (DLN combustor) which changes the combustion process itself.

DLN combustors do exist that burn natural gas but ones using liquid fuel are still in the development stage. This research project is developing a fuel oil type A (JIS K2205 No.1) pre-vaporising, pre-mixing lean-combustion type low NOx combustor.

3.2.2) Research on Technologies for Better Thermal Efficiency

In order to increase significantly thermal efficiency over present levels, research on the following items is being conducted:

i) Use of a regenerative open cycle to recover exhaust energy. To achieve this, research is being conducted on a compact plate-fin recuperator with a large heat transfer surface area for marine use.

ii) Increasing the turbine inlet temperature (TIT) increases thermal efficiency. A TIT target of 1,200°C has been set, which is 50~100°C over that of conventional gas turbines of the same output class. To compensate for these high temperatures, research is being conducted on air-cooled nozzles and blades for the gas generator turbine.

iii) The compressor has a significant influence on thermal efficiency. A highly efficient compressor that combines both axial and radial stages is being developed in preference to the radial compressor widely used by conventional gas turbines in 2MW class.

iv) In an effort to improve thermal efficiency under partial load, a variable type SMGT using the combination of a variable stator vanes of an axial compressor and a variable nozzle of a power turbine is being researched.

3.2.3) Research on Ship Application Technologies

The following themes are being studied regarding applications of gas turbines on ships:

i) Evaluation tests are being conducted on anti-corrosion materials and coatings for the prevention of high-temperature corrosion by sulphur in the fuel and alkaline metals (Na, K, etc.) in the salt-water environment, and low-temperature corrosion due to the salt-water environment.

ii) Research on engine control systems to control engine propulsion characteristics and deal with engine load changes during rough weather, etc.

iii) Research on the influence of ship movement on the gas turbine.

3.2.4) Rig Tests

Based on the above research, a 2,500kW class

SMGT test engines will be produced and tested to evaluate whether they reach their performance goals.

4. R&D Schedule

Figure 3 shows the R&D schedule. In 1997FY, basic overall design work for the gas turbine was completed, and the target goals listed above for each component were developed. Beginning in 1998FY, a variety of tests were carried out on the components. At present, the component test schedule is about halfway complete. An SMGT test engine will be constructed midway through 2001FY , with rig tests scheduled for 2002FY , the final year of the plan.

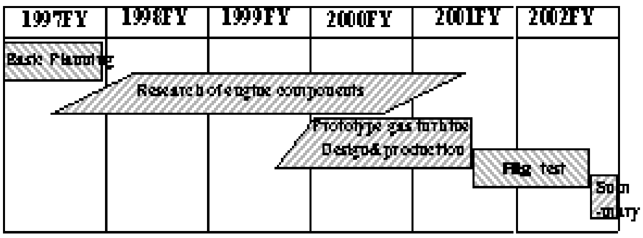


Fig.3 R&D Schedule

5. SMGT Basic Design Specifications

Table 1 shows the targeted design specifications.

Results of the regeneration cycle calculation are shown in figure 4. In order to reach a regeneration cycle of η = 38~40%, a TIT of 1,200°C gives an ideal pressure ratio of (π) = 8.

Figure 5 shows a schematic diagram of the power section.

Combustor types can be broadly divided into two groups: the annular type used in aero-engines, and the can type used in industrial engines. The can type is more flexible with regard to the combustor design for a low N0x structure; maintenance is also simpler. To reduce circumferential temperature distribution, a 4-can type combustor is used.

As mentioned above, the compressor combines four axial stages and a single radial stage. Gas generator turbines (GGT) and power turbines (PT) all use axial turbines.

The recuperator, as mentioned above, is a compact, highly efficient, plate-fin type suitable for use on ships.

Two SMGT types are planned, namely the F-type focusing on the engine's rated load performance, and a V-type focusing on partial load performance. The V-type uses a power turbine with an variable nozzle and a 4-stage axial compressor with variable stator vanes. However, the axial compressors for both the V-type and the F-type will be made interchangeable if it is needed.

The gas turbine will comprise several modules to allow simple transportation and easy maintenance. SMGT research is being carried out based on design and production technologies from industrial gas turbines.

Item		Unit	Specifications	
			F type	V type
Rated power		kW	2,590	2,530
Thermal efficiency		%	39.1	38.4
Air flow rate		kg/s	9.5	
Compressor	Rated speed	rpm	21,000	
	Pressure ratio		8.0	
	Isentropic efficiency	%	84.0	83.7
Recuperator	Temperature effectiveness	%	83.0	
Combustor	Combustor efficiency	%	99.0	
Gas generator turbine	Rated speed	rpm	21,000	
	Turbine Inlet temp.	℃	1,200	
	Isentropic efficiency	%	87.5	
Power turbine	Rated speed	rpm	13,000	
	Isentropic efficiency	%	90.2	89.2
NOx emission		g/kWh	1.0	
		ppm	200 (O_2=0%)	

Table 1 Targeted Design Specifications

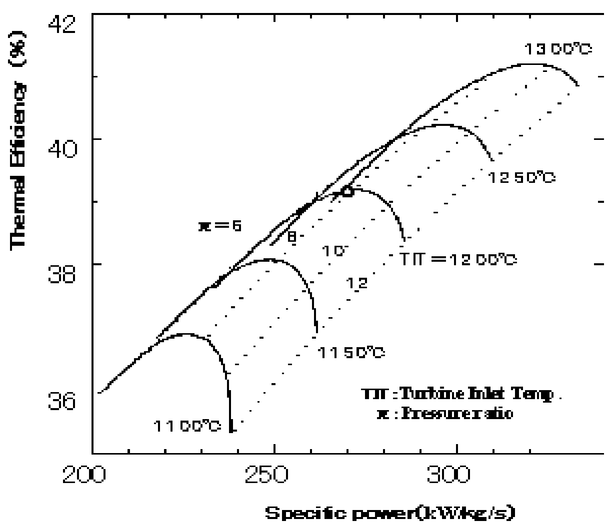


Fig.4 Calculation Results of regenerative cycle

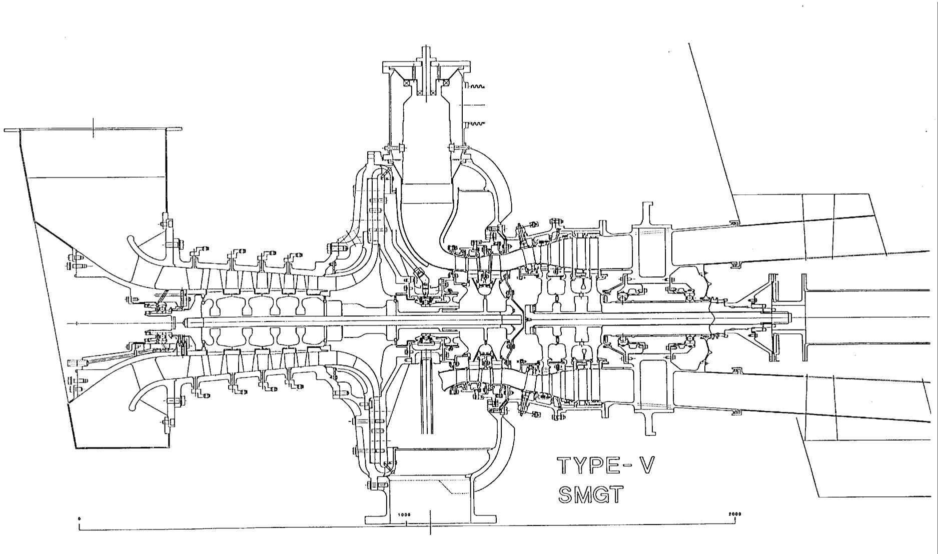


Fig.5 Cross Section of SMGT(V- type)

6. Results and Outline of Component Research

Following are the current conditions and results achieved until now on the research topics listed in 3.2.

6.1 Combustor

The NOx emitted by gas turbines and other internal combustion engines is predominantly thermal NOx created when nitrogen in the air combines with oxygen during high-temperature combustion. When the volume of air is increased and mixed in equal quantities with fuel, lean combustion is achieved, which reduces combustion temperature and lowers the amount of NOx produced.

However, lean combustion may be unstable and incomplete. To achieve stable combustion from light off to full load while also maintaining low N0x over a wide operating range, a variety of ideas and technological developments are needed.

The combustor under development is a 3-burner type using: (1) a pilot burner; (2) a main burner which thoroughly mixes and air fuel using pre-vaporisation and pre-mixing to create a lean mixture); (3) a supplemental burner which burns a fuel mist following main combustion under full load conditions. By increasing the fuel flow rate from light off to full load, the burners are controlled. This maintains low NOx emissions over a wide operating range.

In developing this combustor, a variety of fuel injector nozzle spray patterns were tested, independent burner tests were carried out, and flow modeling experiments were performed to determine in detail the flow inside the combustor. The resulting combustor is now undergoing combustion testing and its N0x emissions and combustor efficiency are being measured and

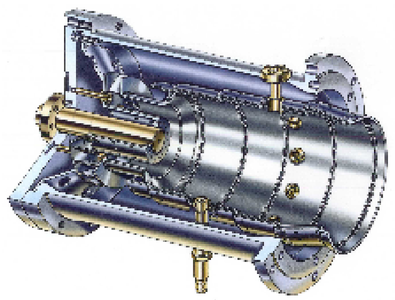


Fig.6 Conceptual Drawing of Combustor

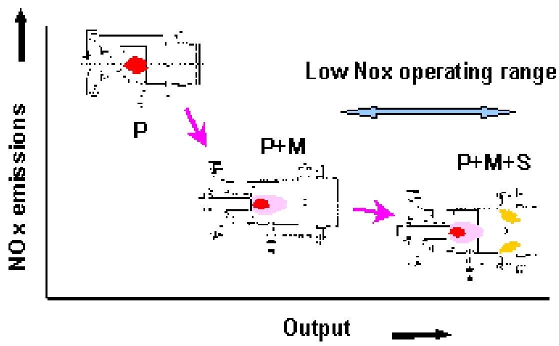


Fig.7 Control of Burner

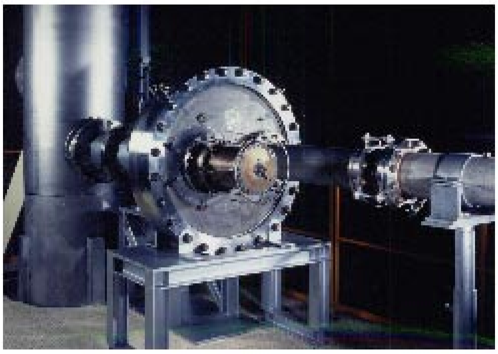


Fig.8 Combustor Test Rig

evaluated.

This research indicates that the target levels can be achieved.

6.2 Recuperator Research

The simple cycle gas turbine engine loses roughly 70% of the heat energy produced in combustion in its exhaust gas. A regenerative cycle which uses this exhaust heat to preheat the air before it goes to the combustor can yield considerable fuel savings.

The plate fin recuperator now being developed uses multiple fins a few millimetres tall between the exhaust gas passageway and the air passageway to stimulate heat exchange.

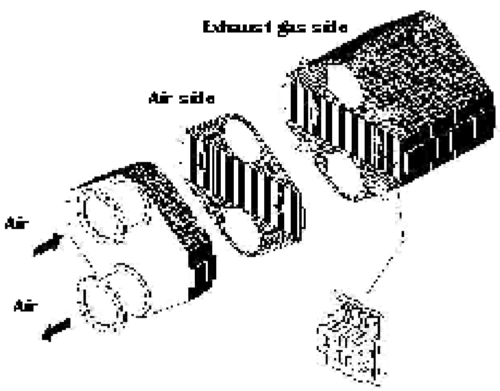


Fig.9 Conceptual drawing of Recuperator (core section)

. During development, heat exchanging performance and thermal stress were analysed and investigated theoretically, and a partial lamination model will be made and tested to evaluate its performance. Through the production and manufacture of this partial lamination model, production technologies are being developed to ensure high reliability and ease of manufacture.

Because temperature effectiveness can be adversely affected by non-uniformity of exhaust gas flow at the recuperator inlet, various shapes for the exhaust diffuser are being tested to ensure uniform flow at the recuperator inlet and thereby determine the ideal shape.

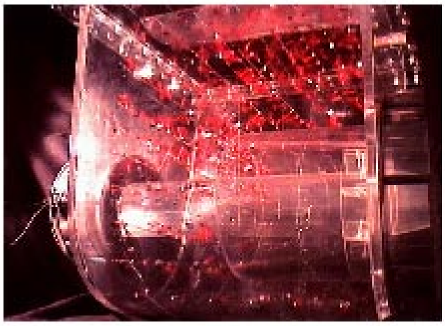


Fig.10 Recuperator Inlet Flow Test

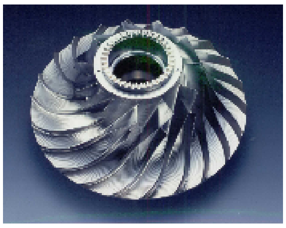
6.3 Compressor

Radial compressors are generally used to handle the airflow rate and pressure ratio of units in 2MW class. They also have a simple structure. However, to achieve high efficiency it is necessary to use the axial type for the low-pressure stage and the radial type for the high-pressure stage.

Because compressor efficiency has such a large influence on overall efficiency, development is being conducted using the latest CFD to analyse cascade flow and a variety of performance tests are being conducted on the axial and radial stages independently and in combination to evaluate compressor performance.

Although testing is still underway, target efficiencies for some of the individual compressors have already been reached.

In addition, research to determine the ideal cascade has been conducted using rotational cascade tests on the first stage of the axial compressor where Mach numbers are highest.



Axial Compressor Rotor (V Type)

Radial Compressor Impeller

Fig.11 Tested Compressors

Fig.12 Axial Compressor Test Rig

Research has also been conducted to discover the ideal shape for the inlet casing to minimise loss and ensure uniform flow at the compressor inlet. The results of these tests are being incorporated into the compressor's design.

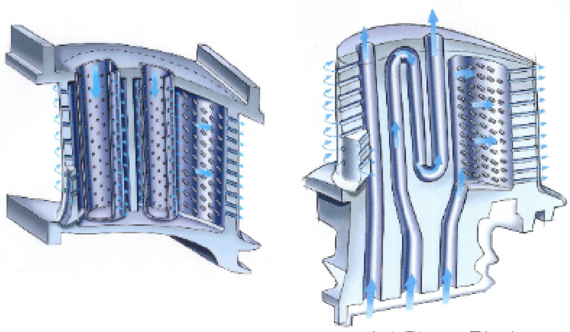
Fig.13 Inlet Casing Flow Test

6.4 Cooled Blades (Gas Generator Turbine)

Advances in materials and blade cooling technologies are permitting yearly temperature increases in gas turbine TIT. However, because the small blade size of low-capacity turbines makes it difficult to machine the complex cooling structure, their blades cannot be cooled as easily as high-capacity gas turbines. This makes it difficult to increase the gas temperature of low-capacity gas turbines.

The SMGT's target TIT of 1,200°C is 50~100°C higher than conventional gas turbines in its class, and more R&D is needed on blade interior structure for efficient cooling of small blades. In conjunction with this, thermal barrier coatings (TBC) which allow higher gas temperatures are also being researched.

This research consists of cooled blade performance analysis and high-temperature cascade tests to measure cooling performance at close to actual temperatures. To gain a detailed understanding of the cooling characteristics of the blade interior, air is flowed through large-scale models of the cooling passageways and their heat conducting properties are tested.



1st Stage Nozzle

1st Stage Blade

Fig.14 Conceptual Drawing of Cooled Blades

6.5 Power Turbine

Two types of power turbine are being developed, the F-type with a fixed nozzle angle and the V-type with a variable nozzle angle at the first stage. As mentioned above, the V-type improves thermal efficiency under partial load. In the case of regenerative cycle gas turbine with a free power turbine, thermal efficiency under partial load can be improved if the recuperator inlet gas temperature is maintained at its rated level when the gas flow rate is reduced to suit a reduction in load. Control of gas flow rate can be accomplished using variable stator vanes. When the stator vane angle is changed, the minimum area between the vanes (throat area) changes, changing the gas flow rate.

Also, there is flow loss in the clearance at the tip of the variable stator vane that does not arise in ordinary turbine structures, so it is important to predict this loss accurately. This is being done by performing annular cascade tests on the variable stator vanes which measure clearance leakage loss and changes in cascade loss caused by altering the flow angle. These results are being applied to the design of the V-type power turbine

6.6 Anti-corrosion Tests

Salt from ocean water may cause corrosion of compressor components, and high-temperature components such as turbine blades may have to cope with corrosion caused by sulphur in the fuel. As a countermeasure, salt spray injection tests and high-temperature corrosion tests were carried out and the anti-corrosion properties of the various materials were tested.

The primary causes of corrosion on turbine blades and other high-temperature components are deposits of Na_2SO_4 formed by sulphur in the fuel and particles of ocean salt. High-temperature corrosion tests simulating actual gas turbine combustion have been carried out on various materials to evaluate their anti-corrosion properties. The results of these tests are being incorporated into the materials used in the SMGT.

The main research topics have been introduced above. In addition, however, when using regenerative cycle gas turbines with a free power turbine for marine applications, transient response to rapid load changes is very important. Simulation model of the SMGT, including its propulsion system, has been created and its transient response characteristics under varying conditions are being studied.

Research will also being conducted on the effects of ship movement on gas turbine components, as well as on operating support system and fault diagnosis system.

7. Conclusion

High development goals have been set for the SMGT, and various researches on all components are needed to achieve these targets. This research has been proceeding smoothly, and future research and rig tests of test turbines will be carried out.

We wish to thank all persons involved for their continuing guidance and assistance.